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TECHNICAL REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the High Performance Commercial Building Systems (HPCBS) Program. This Commercial Building Energy Benchmarking attachment provides supplemental information to the final report (Commission publication # 500-03-097-A2). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is the tenth of 22 technical attachments to the final report, and consists of research reports:

- The Integration of Engineering and Architecture: a Perspective on Natural Ventilation for the new San Francisco Federal Building (E4P2.1T1a3)
- Use of Simulation in the Design of A Large, Naturally Ventilated Office Building (E4P2.1T1a4)

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-012). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit http://www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments are also available at the HPCBS website: http://buildings.lbl.gov/hpcbs/.

Abstract

The Integration of Engineering and Architecture: A Perspective on Natural Ventilation for the New San Francisco Federal Building

A description of the in-progress design of a new Federal Office Building for San Francisco is used to illustrate a number of issues arising in the design of large, naturally ventilated office buildings. These issues include the need for an integrated approach to design involving the architects, mechanical and structural engineers, lighting designers and specialist simulation modelers. In particular, the use of natural ventilation, and the avoidance of air-conditioning, depends on the high degree of exposed thermal mass made possible by the structural scheme and by the minimization of solar heat gains while maintaining the good daylighting that results from optimization of the façade. Another issue was the need for a radical change in interior space planning in order to enhance the natural ventilation; all the individual enclosed offices are located along the central spine of each floorplate rather than at the perimeter. The role of integration in deterring the undermining of the design through value engineering is discussed. The comfort criteria for the building were established based on the recent extension to the ASHRAE comfort standard based on the adaptive model for naturally ventilated buildings. The building energy simulation program EnergyPlus was used to compare the performance of different natural ventilation strategies. The results indicate that, in the San Francisco climate, wind-driven ventilation provides sufficient nocturnal cooling to maintain comfortable conditions and that external chimneys do not provide significant additional ventilation at times when it when it would be beneficial.

Use Of Simulation In The Design Of A Large, Naturally Ventilated Office Building

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. The EnergyPlus thermal simulation program was used to evaluate different ventilation strategies for space cooling and rationalize the design of the facade. The strategies include ventilation driven by different combinations of wind, internal stack and external stack. The simulation results indicate that the wind-driven ventilation can maintain adequate comfort even during hot periods. Computational fluid dynamics was used to study the airflow and temperature distribution in the occupied spaces arising from different combinations of window openings and outside conditions and thereby inform both the design of the windows and control strategy.

Design and Testing of a Control Strategy for a Large Naturally Ventilated Office Building

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. Each floor is designed to be cross-ventilated, through upper windows that are controlled by the building management system (BMS). Users have control over lower windows, which can be as much as 50% of the total openable area. There are significant differences in the performance and the control of the windward and leeward sides of the building, and separate monitoring and control strategies are determined for each side. The performance and control of the building has been designed and tested using a modified version of EnergyPlus. Results from studies with EnergyPlus and CFD are used in designing the control strategy. EnergyPlus was extended to model a simplified version of the airflow pattern determined using CFD. Wind-driven cross-ventilation produces a main jet through the upper

openings of the building, across the ceiling from the windward to the leeward side. Below this jet, the occupied regions are subject to a recirculating airflow. Results show that temperatures within the building are predicted to be satisfactory, provided a suitable control strategy is implemented uses night cooling in periods of hot weather. The control strategy has 10 window opening modes. EnergyPlus was extended to simulate the effects of these modes, and to assess the effects of different forms of user behavior. The results show how user behavior can significantly influence the building performance. Simplified models for heat transfer in rooms

The goal of the research presented in this thesis is to develop a better understanding of the important parameters in the performance of ventilation systems and to develop simplified convective heat transfer models. The general approach used in this study seeks to capture the dominant physical processes for these problems with first order precision, and develop simple models that show the correct system behavior trends. Dimensional analysis, in conjunction with simple momentum and energy conservation, scaled model experiments and numerical simulations, are used to improve airflow and heat transfer rate predictions in both single and multi room ventilation systems. This study includes the three commonly used room ventilation modes: mixing, displacement and cross-ventilation. The implementation of the models in a building thermal simulation software tool is presented as well as comparisons between model predictions, experimental results and complex simulation methods. The improved precision of the new models, when compared with currently available simple models is clearly displayed.

California Energy Commission
Public Interest Energy Research Program

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HPCBS

High Performance Commercial Building Systems

The Integration of Engineering and Architecture: A Perspective on Natural Ventilation for the New San Francisco Federal Building

Element 4
Project 2.1
Task 2.3.1

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Abstract

A description of the in-progress design of a new Federal Office Building for San Francisco is used to illustrate a number of issues arising in the design of large, naturally ventilated office buildings. These issues include the need for an integrated approach to design involving the architects, mechanical and structural engineers, lighting designers and specialist simulation modelers. In particular, the use of natural ventilation, and the avoidance of air-conditioning, depends on the high degree of exposed thermal mass made possible by the structural scheme and by the minimization of solar heat gains while maintaining the good daylighting that results from optimization of the façade. Another issue was the need for a radical change in interior space planning in order to enhance the natural ventilation; all the individual enclosed offices are located along the central spine of each floorplate rather than at the perimeter. The role of integration in deterring the undermining of the design through value engineering is discussed. The comfort criteria for the building were established based on the recent extension to the ASHRAE comfort standard based on the adaptive model for naturally ventilated buildings. The building energy simulation program EnergyPlus was used to compare the performance of different natural ventilation strategies. The results indicate that, in the San Francisco climate, wind-driven ventilation provides sufficient nocturnal cooling to maintain comfortable conditions and that external chimneys do not provide significant additional ventilation at times when it when it would be beneficial.

Introduction

In 1998, the commission for a new federal office building in San Francisco was awarded based on the result of a competitive design process managed by the Design Excellence Program of the General Services Administration (G.S.A.). Among other goals, the program seeks to "produce facilities that reflect the dignity, enterprise, vigor, and stability of the Federal government, emphasizing designs that embody the finest contemporary architectural thought." Further, the G.S.A. is explicitly committed to "incorporating principles of sustainable design and energy efficiency into all of its building projects."

Design work began in earnest in September, 2000. Broadly understood, the design of the new San Francisco Federal Office Building grew and evolved around three primary organizing concepts:

- the design of a building that offers dramatically reduced energy consumption through the integration of architecture and sustainable engineering principles;
- the creation of office environments that influence the productivity and health of the working population through natural ventilation, operable windows, and daylit interiors;

- the redefinition of the circulation and vertical movement paths in the building, using innovative elevators, three-story sky lobbies, and compelling stairways to promote walking throughout the building.

Considered together, the principles that have guided the design will yield significant operational and life-cycle cost benefit. Together with the G.S.A., the design team recognized the importance of a developing a flexible, intelligent, efficient, aesthetically significant building, one that serves the needs of the Federal government for generations to come.

The Potential

With a site located in downtown San Francisco, California, the temperate outdoor air temperatures (the monthly mean maximum temperature for September, which is the hottest month, is 75°F) prompted early discussions within the design team about the possibility of a naturally ventilated building. A study into the wind climate showed a strong prevailing wind condition from the west-northwest.

Given the favorable climatic conditions, the architectural team did further research into the occupant-perceived benefits of naturally ventilated buildings. Theses benefits have been clearly recognized by architects, engineers, facilities managers, and building owners in recent years. The expected advantages of by naturally ventilated buildings include increased worker productivity, lower turnover in the workforce, and fewer health issues, in contrast to the documented ventilation problems with sealed building envelopes. Additional benefits are expected to accrue from the extensive daylighting that has been included in the final design of the building.

The Implications

Building on the inherent climatic potential, the benefits to the occupants, and the potential to reduce energy use, the team moved forward with a careful and deliberate investigation into the implications of designing a naturally ventilated office building in a society that is used to fully air-conditioned ones. The issues included:

- the need to clearly explain intent and obtain early and strong client support for the organizing principles;
- the need to address the security and life-safety concerns associated with operable façade elements;
- the need for an integrated approach to design involving the architects, mechanical engineers, structural engineers, curtain wall consultants, electrical engineers and lighting designers;
- the need to embed the architectural language of the building within the mechanical and structural engineering concepts, inextricably binding each element of the building;
- the need for a radical change in interior space planning in order to enhance the natural ventilation cross-flow potential;
- the need to understand the most recent research into perceptions of comfort in naturally ventilated buildings and to involve specialist simulation modelers in the prediction of internal temperature and air speed conditions;

- the need to change the traditional paradigm that separates architectural design from interior design, since the design characteristics of the office furniture will have a direct bearing on the performance of the natural ventilation.

Client Support

With eight different federal tenant agencies involved, the team faced a considerable challenge in communicating the ideas behind the building to a wide variety of users, many with competing visions of how the new building should operate. Early in the process, key individuals in each agency were identified and included in substantive working sessions on the design concept. In this way, the architect and engineers were able to anticipate issues about the flexibility of the building, become familiar with the management problems that are associated with new construction and commissioning, and understand the very real concerns that the agency managers had about maintaining proper comfort levels in the building. Through these meetings, tenant representatives came to understand and appreciate the clear benefits that would be provided through the natural ventilation design.

While these detailed client meetings were taking place, the team also endeavored to communicate the detailed evolution of each component of the building to the owner. Review sessions with key G.S.A. engineers in the approval process for each discipline were undertaken to ensure that the natural ventilation concept was emerging in an open, engaged atmosphere. At each juncture in the approval process, the client was also kept informed of the overall energy consumption projections. In this way, the overarching goal of producing a highly efficient building was continually highlighted as a critical component of the process, helping to ensure the eventual approvals required for the project to proceed.

Security and Life-Safety Issues

Having the support of the General Services Administration for the principle of natural ventilation in this building on this site was instrumental in allowing the team to move forward with specific issues, including security and life safety. As with all buildings built under the aegis of the G.S.A., this federal office building is required to establish a "hard" (i.e., impenetrable) perimeter at the base of the building. Additionally, all outside air intakes into the building are well removed from easy access and all structure is designed with blast-resistance in mind. Despite the appeal of a building that could open up in response to the environment, security concerns mandate that the lower, more vulnerable floors be completely sealed. Thus, to achieve natural ventilation, a high-rise building was proposed with natural ventilation as the primary means of cooling on levels 6-18 and full air-conditioning on the lower levels.

This high-rise solution triggered a different set of challenges in the form of the smoke control code for high-rise buildings. The current Uniform Building Code and National Fire Code promote the compartmentalization of high-rise buildings in order to contain the generated smoke within the fire zone itself. This strategy is often accomplished by using the air conditioning system fans to pressurize adjacent zones with dedicated extract of smoke from the fire floor. A naturally-ventilated building with operable windows, then, presents a problem in that there is no air-conditioning system to assist with pressurization. Moreover, there are operable windows in the façade itself that may allow smoke to migrate up the exterior of the building.

In response to this challenge, the motorized window actuators are supplied from the emergency power circuit to close the windows in the event of a fire. Secondly, low voltage hold open options for the manual windows are currently under investigation, with gravity-driven closure upon loss of power to the electromagnets. Last but not least, the trickle vents are located at the floor slab, with very small openings. It is not currently anticipated that the amount of smoke leaving the fire floor through these vents would be significant enough to be detrimental to the air quality in the adjacent floors.

The final question in the life-safety category relates to the provision of minimum outside air for the internal areas of the 20 m (66') wide floor plate. The plan width was so designed on the assumption that the 6m (20') closest to the perimeter would be naturally ventilated, in keeping with industry's understanding of the penetration distance for single-sided natural ventilation, as exemplified by the current practice in California's Energy Code that allows a space to be considered naturally ventilated only if every part of the space is within 6m (20') of an operable element in the façade. Since the structural cores themselves would be on the order of 6m (20') deep for a high-rise building of this height, the floorplate naturally divided into two strips of naturally ventilated zones along the perimeter, separated by a spine of enclosed conference rooms, offices, restrooms, and break areas, which would have a constant supply of mechanical ventilation to ensure indoor air quality.

Integrated Design and Embedded Architecture

The design team sought to work in an environment of extremely close collaboration, challenging design assumptions across ALL disciplines in order to derive a thoroughly integrated solution, augmenting the emphasis from Jones and West (2001) regarding the "highly cooperative effort from the architect and indoor environmental engineer." In fact, this multi-disciplinary type of intimate interaction is essential to the realization of a successful naturally ventilated building, as each discipline's design proposals have an impact on all the other disciplines in a cascading fashion. For instance, one decision about glazing that allows more light into the building might also simultaneously increase the solar gain to the point where the cooling from outside air alone will not be sufficient to keep indoor conditions comfortable. This would cause the mechanical engineer to introduce an air-conditioning system, which would then add electrical load on the building. On this project, this conflict was identified early in the process, acknowledging that high solar gains through the glass of the southeast façade would not only be uncomfortable for the occupants but may serve to deplete the thermal mass of its charge during the morning hours through long-wave radiative exchange between the warmed low level surfaces and the night-cooled thermal mass above. Thus the exterior shade was introduced not only to provide solar protection but also to allow for a form-based visible architecture with a standard repeatable floorplan. Additionally, fins perpendicular to the northwest façade were introduced to intercept direct solar radiation during the afternoon hours when the sun would otherwise fall on the glazing simultaneous to the peak outdoor air temperatures.

In another example of multi-disciplinary integration, the structural system in the main tower employs an upstand beam—non-standard in most concrete construction. However, a downstand beam in the same perimeter location would effectively detach the airflow from the slab during the night pre-cooling and lessen the effectiveness of the thermal mass (see **Figure 1**). In a similar manner, the downstand beam was disrupting the penetration of daylight from the façade. With the improved penetration of daylight as confirmed by the lighting consultant's daylighting analysis, all perimeter zones could be designed with daylighting controls to dim the ambient artificial lighting whenever possible, allowing individuals to control a limited amount of local task lighting when performing tasks requiring more visual acuity.

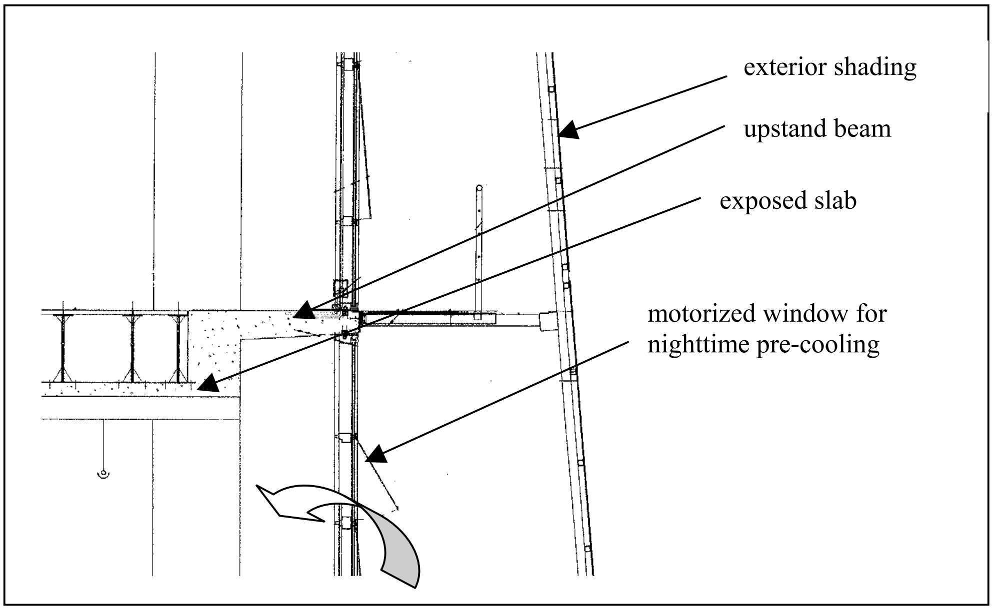

Figure 1. Section through slab/façade detail.

Furthermore, a useful byproduct of the upstand beam approach is the creation of an underfloor plenum. With removable floor tiles above, the plenum offers flexibility in the routing of telecommunications and electrical power conduit, easy access to the main piping routes, and space for underfloor air distribution in the lower sealed floors of the building and at the central spine of enclosed offices at each naturally ventilated floor. This underfloor air distribution scheme at the upper floors meant that the lid ceilings of the enclosed offices could remain thin, thereby creating a gap through which the two naturally-ventilated sides of the building could experience cross-flow under favorable wind conditions and the full slab could be pre-cooled in the nighttime purge of structural heat. The use of natural ventilation for nocturnal pre-cooling and the factors influencing performance are discussed by Martin and Fletcher (1996) and by Kolokotroni (2001).

A last example of integrated design and embedded architecture involves the sophisticated use of the multi-part window wall at the naturally ventilated areas. Besides the straightforward coordination to meet the glazing performance necessary for the comfort and lighting requirements, the curtain wall designer also integrated window actuators into the mullions and trickle vents at the base. Moreover, the architect and window wall consultant worked with the mechanical, electrical and structural engineers to develop a set of details that would allow the following "clean" window wall aesthetic:

- finned tube heating convectors mounted in the curtain wall mullion depth with dedicated pipe-bypass areas built into the mullions to minimize the visibility of piping, but maintaining proper access for servicing;

- conduit and pull-boxes integrated into the mullion system to allow a hidden route for electrical power wiring and low-voltage control wiring to the motorized window actuators;
- dedicated trenches and sleeves at each column bay within the structural slab to allow for piping and conduit to pass from the underfloor plenum area to the perimeter curtain wall zone.

Throughout the process, the team sought to continually strengthen the owner's perception of the building as an "integrated design," one that binds the architectural, engineering, and urban design goals tightly together. Most significantly, the architectural aesthetic has been intertwined with the engineering decisions made to minimize energy use. This approach was explicitly engaged to deter the possibility that the sustainability goals be abandoned at a later point in the design process through value engineering. Two rigorous value engineering sessions with independent peer auditors were completed during the design development phase; these reviews have confirmed the intelligence of this initial strategy.

Changes to Interior Space Planning

For the client/user group, the most challenging initiative in the design of the building has been the revision of the rules for the interior space planning. In order to enhance the benefit of the natural ventilation scheme in the tower, all individual offices at the perimeter of the floorplate have been eliminated, with open work stations lining the window walls on the southeast and northwest walls. All closed offices, conference spaces, and other private environments have been located along a central spine of each floorplate. This arrangement of interior spaces required detailed discussion with the client and tenant agencies about the inherent tradeoffs between two opposing realities: traditional hierarchical office culture on the one hand; fresh air, occupant control, and daylit interiors on the other. Finally, it is important to note that those agencies with intensive computer use or requiring air-conditioning are located in the sealed lower floors of the building.

Perception of Comfort

Natural ventilation is an umbrella term that usually refers to an airflow scheme in which air is provided directly from outdoors into an occupied space for any one or all of the following purposes:

- minimum ventilation: the process by which outside air is provided to an occupied space to maintain a minimal level of indoor air quality;
- night purge of structural heat: the process by which "freely-cooled" nighttime air is intentionally allowed into the unoccupied building in order to reduce the surface temperature of exposed concrete thermal mass inside;
- thermal comfort: the process by which air flow creates an acceptable indoor environment, both by replacing hot indoor air with cooler outdoor air and producing enhanced heat transfer at the skin.

The first two uses of natural ventilation are fairly straightforward and have been mentioned earlier in this paper. The use of natural ventilation for the last reason—thermal comfort -- requires more elaboration as it requires the occupant to understand that, unlike an air-conditioned space, a naturally ventilated building does not automatically adjust itself to control indoor temperature to a fixed set-point.

Thermal comfort in fully air-conditioned buildings is usually calculated using a static model. Such a model defines one thermal comfort temperature, referred to as a neutral temperature, as a quantifiable standard of comfort, independent of the building's location and climate. For example, the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE, 2001) defines "… standard specified conditions or comfort zones where 80% of sedentary or slightly active persons find the environment thermally acceptable." Recently, however, it has been argued (Brager, 2000) that "The standard was originally developed through laboratory tests of perceived thermal comfort, with the limited intent to establish optimum HVAC levels for fully climate-controlled buildings. However, in the absence of any credible alternative, Standard 55 is applied universally across *all* building types, climates and populations."

ASHRAE is currently in the process of extending its comfort standard (Standard 55) to include an 'adaptive model' for naturally ventilated buildings. The model is based on a large dataset of field observations that showed that "occupants of naturally ventilated buildings appear tolerant of—and, in fact, prefer—a wider range of temperature" than their counterparts within fully air-conditioned buildings. Of particular interest is that "behavioral adaptations, such as changes in clothing insulation or indoor air speeds, could account for only half the observed variance in thermal preferences. . .this suggested the rest of the variance was attributable to psychological factors. Chief among these was a relaxation of thermal expectations, possibly because of a combination of high levels of perceived control and a greater diversity of thermal experiences in the building." (Brager and de Dear 2000)

The design team proposed to the General Services Administration that the naturally ventilated portions of the new Federal Office Building should have design criteria in compliance with the proposed adaptive model, which links the indoor comfort temperature to the mean monthly outdoor air temperature, as shown in **Figure 2**.

Therefore the design of the natural ventilated areas within the San Francisco Federal building uses the adaptive model as the design criteria and will attempt to limit the range of indoor comfort temperatures to the 80% acceptability limits shown in **Figure 3**. The upper limit on the 80% acceptable range is 79-82°F for the cooling season (April 1-October 31).

Note that the 'comfort temperature' used in the standard is the indoor dry bulb rather than a composite temperature, such as operative temperature, that includes radiative effects. This is because the field measurements on which the adaptive model is based generally include dry bulb temperature but not radiant temperature.

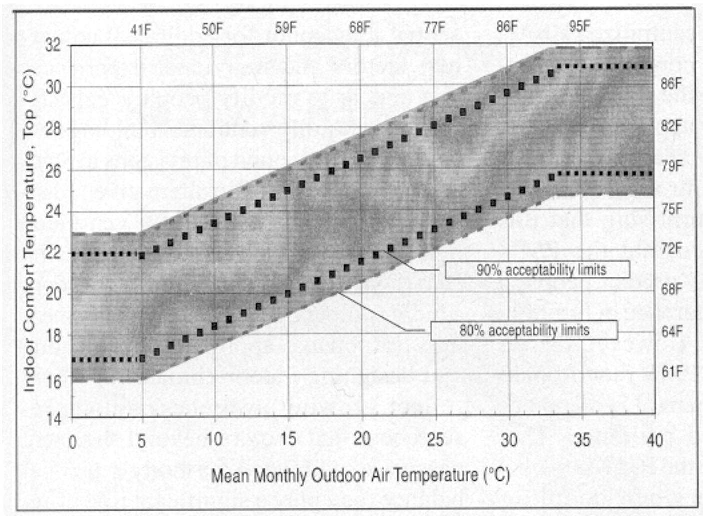

Figure 2. Proposed adaptive standard for comfort in naturally ventilated buildings (Source: Brager and de Dear 2000).

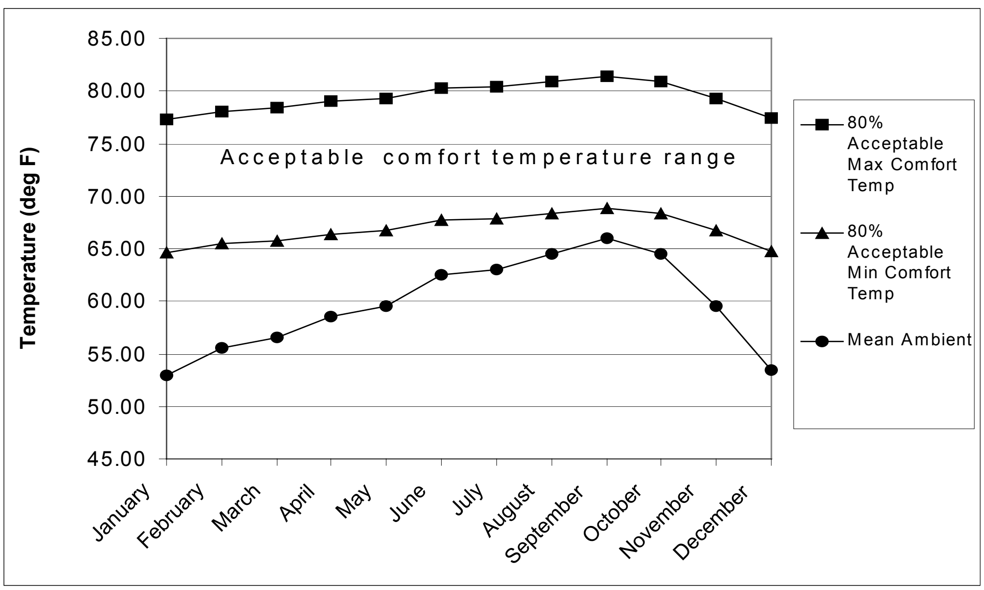

Figure 3. Monthly mean maximum, minimum and average temperatures for San Francisco and the 80% acceptability limits derived from Figure 2.

Assessment of Natural Ventilation Design Options

Having established the design target, it was then necessary to perform predictive simulations of indoor comfort temperature to see if the target was met. Lawrence Berkeley National Laboratory was commissioned to evaluate several natural ventilation strategies. In support of the conceptual design phase, several natural ventilation strategies were evaluated using a beta release of DOE's new building energy simulation program, EnergyPlus (Crawley et al. 2000), which includes the multizone air-flow model COMIS (Huang et al. 1999). The aim was to compare the ability of the different window configurations to maintain comfort during hot summer conditions. The strategies were:

- **wind only:** Continuous openings along both the NW and SE facades at the same height. Since the openings are at the same height, there is no buoyancy-driven flow.
- **internal stack:** Continuous openings at floor level on the NW façade and at ceiling level on the SE façade, which produces an internal stack; there are no wind effects.
- **internal and external stack:** Continuous openings at floor level on the NW façade, high openings into three story high chimneys on the SE façade, no wind effects
- **internal stack + wind:** Continuous openings at floor level on the NW façade and at ceiling level on the SE façade. The flow is produced by a combination of wind and internal stack effects.
- **internal and external stack + wind:** Continuous openings at floor level on the NW façade, high openings into three story high chimneys on the SE façade. The flow is produced by a combination of wind and internal and external stack effects.

A representative 9m section of one open plan office floor was modeled as a single thermal zone, including the appropriate internal and solar heat gains. The external chimney, when present, was modeled as a second thermal zone. A discharge coefficient of 0.5 was assumed for each opening (a conservative value that allows for pressure drop through the scrim) and pressure coefficients were estimated from data in Chapter 15 of the ASHRAE Handbook of Fundamentals (ASHRAE 2001). The different window configurations were simulated for the period April 1 to October 31 of the TMY2 composite weather year for San Francisco International Airport. A comparison of the meteorological conditions at the site to those at the airport indicated that summer-time maximum temperatures are a few degrees centigrade lower at the site, whereas minimum temperatures and wind speed and direction are essentially equal within the uncertainties of the information available. Use of airport data for cooling assessment is therefore considered to be conservative.

The predicted indoor temperatures were analyzed to produce **Table 1**, which shows the number of hours when the listed base temperature was exceeded during the occupied hours during the cooling season. When reviewing these data, it is important to recall that the upper limit design criterion is 79-82^{o}F for the cooling season. The case of no ventilation is also shown for comparison. The main conclusions are:

1. Wind-driven night ventilation produces reasonable comfort conditions during the day for all but a few days of a typical year.
2. Internal stack-driven night ventilation resulting from low level openings on the NW and high level openings on the SE is less effective than wind-driven ventilation, resulting in internal temperatures on hotter days that are ~1^{o}F higher than for the wind-driven case.
3. A combination of wind-driven and internal stack-driven ventilation produces a modest improvement in performance compared to the wind only case. The contribution of internal stack may be more significant if/where there is significant reduction is wind pressure due to shielding by adjacent buildings.
4. Addition of external chimneys does not improve the performance of the combination of wind-driven and internal stack-driven ventilation, and may be slightly counter-productive, due to the increased flow resistance caused by the chimney. In the absence of wind, addition of external chimneys helps the internal stack somewhat.

On the basis of this analysis, the design team decided that those funds which were allocated to the construction of the chimneys could be better used to provide high performance, double-glazed low-e glass on both northwest and southeast façade, thereby minimizing the heating loads and lending to higher level of indoor comfort through improved solar heat gain coefficient.

Table 1. Occupied Hours Above Various Base Temperatures

Base temperature (^oF)	Wind only	Internal stack	Int & ext stack	Int stack + wind	Int & ext stack + wind	No ventilation
72	288	507	432	279	285	14561
75	80	118	103	76	76	8894
78	13	25	19	11	12	4284

Having established that the building in general has sufficient thermal capacity and natural ventilation openings to achieve the indoor temperature design criterion, the analysis proceeded to examine the building's behavior on a worst-case day.

The indoor comfort temperature exceeds 78^{o}F on six particularly hot days during the typical year, when the maximum ambient air temperature is in the range 86-95^{o}F. **Figure 4** shows the predicted performance of the different strategies on one of these days, July 3, 1970, which was the third day of a sequence of three extreme days; the preceding two days had maximum temperatures of 86^{o}F and 95^{o}F. As a result, the building was not significantly precooled at the beginning of the occupancy period, as nighttime temperatures also remained high. The rise in internal temperature during the first eight hours of occupancy is limited only by the thermal capacity of the building, since the outside temperature is too high for ventilation to be useful. The cases in which the wind is supplemented by internal or external stack effects have temperatures that would not easily be distinguished from the wind only case in **Figure 4** and have been omitted for clarity. Similarly, the internal plus external stack case has been omitted since it is difficult to distinguish from the internal stack case.

The version of EnergyPlus that was used in the preliminary assessment was a relatively early version and a number of 'bugs' have subsequently been found in the program that affect the absolute prediction of the space temperatures used to generate **Table 1** and **Figure 4**. However, subsequent studies of the sensitivity of the space temperatures to the ventilation rate confirm the basic conclusion of the preliminary assessment, i.e., that the airflow rates generated by wind pressure could be substantially reduced before the ventilation rate became the limiting factor in performance.

In support of detailed design, a more detailed simulation model was developed, which included the following features:

- separate zones for the open plan work areas on the NW and SE sides of the floor;
- an average vertical clearance between the top of the enclosed 'cabins' and the underside of the exposed ceiling slab of 0.5m;
- two operable openings on each façade, one at desk height (0.8m) and one at ceiling height (3.3m), the open aperture of each opening being restricted to 100mm;

- pressure coefficients, measured in a wind tunnel, for a location in the tower selected to have a low wind pressure difference between the NW and SE facades;
- approximated treatment of the angular dependence of the optical transmission of the scrim on the SE façade;
- a glazing system consisting of an outer layer of 6mm glass with a low emissivity, spectrally selective coating and an inner layer of blast-resistant, laminated glass, the system having a visible light transmission of 0.6 at normal incidence and a Solar Heat Gain Coefficient of 0.3.

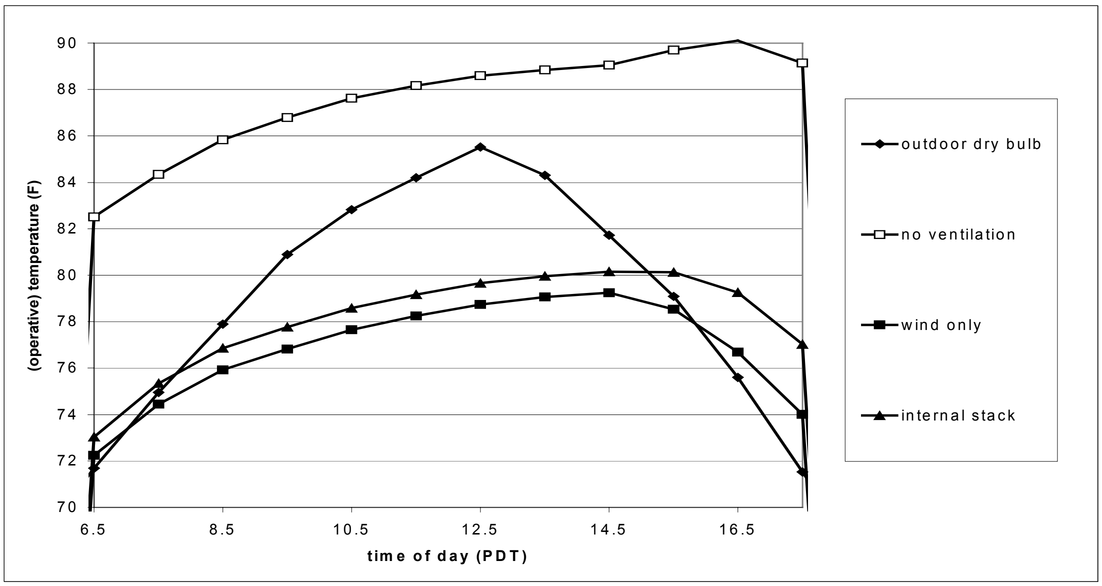

Figure 4. Relative performance on the third of a sequence of hot days.

The performance trends under very hot weather conditions predicted by the detailed model are quite similar to that predicted by the initial model, but the current version of EnergyPlus (V1.0.0.1, Build 10), predicts that there will be ~38 weekday hours per year above 78^{o}F.

The performance of the natural ventilation system is limited by the amount of exposed thermal capacity and the magnitude of the daytime gains, particularly solar gains. The major difference between the preliminary model and the detailed model is the treatment of the enclosed cabins. A major effect of the cabins is to largely decouple the thermal capacity of the exposed slab above the cabins from the open plan spaces and hence reduce the effective thermal capacity by ~33%. Compensating improvements have come from an improved glazing system and treatment of the off-axis transmission of the scrim.

There are indications that reducing the transmissivity of the glazing system would improve cooling performance under very hot weather conditions without a significant adverse impact on the daylighting. However, this issue needs to be considered in the broader context of the daylighting in the space and the possibility of using dimming controls for the lights above the inner row of workstations on the NW side. The current models assume operable blinds on the NW façade; other options for solar control on the NW façade will be considered within the broader context of the lighting and daylighting aspects of the design.

Conclusions and Future Work

Building on the current results that show comfortable conditions for the vast majority of occupiable hours in the year, more detailed modeling, in the form of the computational fluid dynamics (CFD) currently under way. Coincident with this study will be a review of the most recent EnergyPlus model's behavior, as it will be providing nominal surface temperature boundary conditions for the CFD. This further set of analyses is intended to address the question of ventilation effectiveness in the workstations on the leeward side of the full height service cores and air velocities at the windward side façade openings. The detailed air-velocity and temperature distributions in these specific areas, when taken with the radiant temperature data from EnergyPlus, will be able to give the design team an overall picture of the acceptability of the naturally ventilated environments in these particular "worst-case" local zones.

Additionally, a CFD sensitivity analysis of internal air velocities versus various outdoor wind speeds will allow the control algorithm for the motorized windows to be developed in the next phase of the design. Current explorations include such features as:

- monitoring differential pressure across the floor width in order to select the temperature sensed at the current lee-side of the cabin areas as the dominant feedback.
- using the National Weather Service Internet forecasts to provide a prediction of the next day's peak temperature as an input to the window control sequence for nighttime purge of heat from the thermal mass
- dedicated trenches and sleeves at each column bay within the structural slab to allow for piping and conduit to pass from the underfloor plenum area to the perimeter curtain wall zone.

Acknowledgment

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High Performance Commercial Building Systems

Use of Simulation in the Design of a Large Naturally Ventilated Commercial Office Building

Element 4   Low Energy Cooling

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USE OF SIMULATION IN THE DESIGN OF A LARGE NATURALLY VENTILATED COMMERCIAL OFFICE BUILDING

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ABSTRACT

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. The EnergyPlus thermal simulation program was used to evaluate different ventilation strategies for space cooling and rationalize the design of the façade. The strategies include ventilation driven by different combinations of wind, internal stack and external stack. The simulation results indicate that wind-driven ventilation can maintain adequate comfort even during hot periods. Computational fluid dynamics was used to study the airflow and temperature distribution in the occupied spaces arising from different combinations of window openings and outside conditions and thereby inform both the design of the windows and the control strategy.

INTRODUCTION

A new Federal Building for San Francisco is currently under construction. The open-plan office spaces that comprise the majority of the building will be naturally ventilated, with no mechanical ventilation or cooling (McConahey *et al.*, 2001). The EnergyPlus building energy simulation program, (Crawley *et al.,* 2001) has been used to support the initial design of the building by simulating the performance of a number of different natural ventilation strategies, as described below. The paper also describes the use of computational fluid dynamics (CFD) to study the airflow and temperature distribution in the occupied spaces arising from different combinations of window openings and outside conditions. The design of the control strategy, and the use of EnergyPlus and CFD in informing and in testing the strategy, are described in a companion paper (Carrilho da Graça *et al.*, 2003).

The part of the building that contains the naturally ventilated spaces is a narrow plan high-rise tower, elongated in the NE-SW direction. Plans and sections of a typical floor are shown in Figures 1 and 2. The width of the building is 19 m and the height of the exposed, high-mass ceiling slab is 3.3 m above the raised access floor. The central third of the floor plan consists of stairwells, elevator shafts, bathrooms and air-conditioned conference rooms. Air can flow from one side of the floor to the other through corridors and above the conference rooms and bathrooms. The SE façade is articulated by a perforated metal scrim external to the glazing, which also serves to reduce the solar gain by ~50%.

CLIMATE

The simulations were performed using the TMY2 meteorological data measured at San Francisco International Airport. A comparison of the measured wind regimes at the building site in downtown San Francisco and at the airport, indicates that the wind speed and direction at the gradient height of the atmospheric boundary layer at each location are not significantly different. It is then only necessary to allow for the effects of the urban terrain, which is done by assuming a wind velocity profile exponent of 0.14. A comparison of the ambient temperature measurements for the two locations indicates that summer daytime temperatures are 2-4K lower at the building site than the airport, while summer night-time temperatures are approximately equal at the two sites. This indicates that using meteorological data measured at the airport is slightly conservative. Issues relating to climate change have not been addressed.

Figure 3 shows the variation of ambient dry bulb temperature during the warmer half of the TMY2 year. On most days, the maximum temperature does not exceed 21^{o}C and only for a few limited periods is it over 27^{o}C. These periods, which typically do not exceed three days, are the periods for which there is the most significant risk of overheating.

SELECTION OF NATURAL VENTILATION SCHEME

Two initial questions facing the design team were:

1. Is there is a need to use buoyancy effects arising from inside-outside temperature differences to supplement the wind?

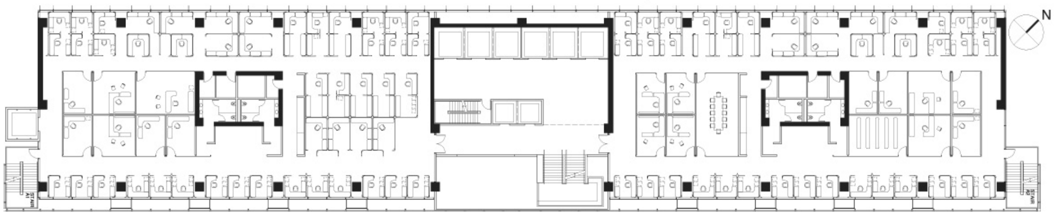

Figure 1. Plan of a typical floor. The building is 122m long and 19m wide.

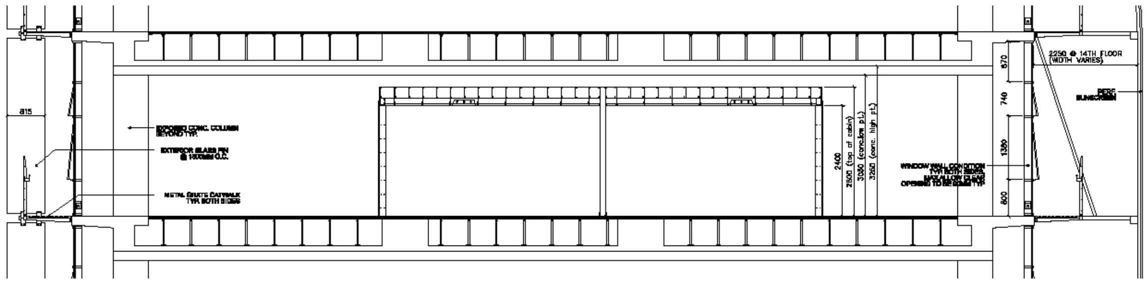

Figure 2. Section of a typical floor of the SFFB. The NW is on the left. The meeting rooms in the center are conditioned and reach a height of 2.8m, leaving a gap that allows for air passage.

2. If there is such a need, is the stack-driven flow resulting from the use of high and low openings within the height confines of a single floor sufficient, or are sources of additional buoyancy, such as external chimneys on the SE façade, required to give acceptable thermal performance?

These questions were addressed by using EnergyPlus to simulate different natural ventilation strategies involving different combinations of wind and buoyancy-driven flow.

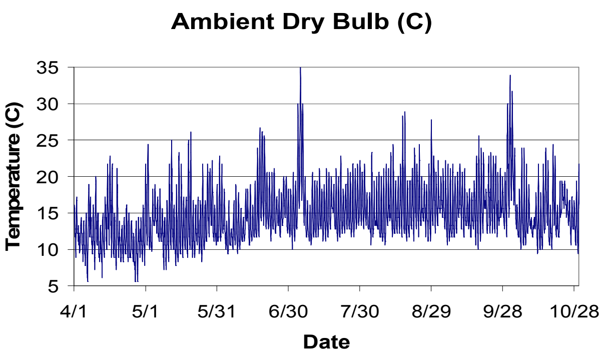

Figure 3: Ambient dry bulb temperature from April to October from the TMY2 for San Francisco airport

Modeling

EnergyPlus is a whole building energy simulation program that predicts interior thermal conditions by simultaneously solving heat balance equations for the surfaces and room air in each enclosed space. Convective and long wave and short wave radiative transfer are treated separately and explicitly. Daylighting and lighting controls are modeled in order to allow the effects of choice of glazing and window control strategy on artificial lighting use and solar heat gain to be investigated. The COMIS interzone airflow simulation has been integrated into EnergyPlus (Huang, 1999), allowing ventilation rates, and their thermal consequences, to be recalculated at each time-step. Ventilation rates are calculated by solving a network consisting of nodes connected by flow elements that correspond to openings between spaces and between spaces and the outside. Buoyancy-driven flows are predicted using space temperatures calculated at the previous time-step; there is no iteration between the air-flow and thermal calculations. A time-step of 15 minutes was used in the simulations.

The strategies modeled were:

– **wind only –** continuous openings along both the NW and SE facades at the same height. Since the openings are at the same height, there is no buoyancy-driven flow.

– **internal stack -** continuous openings at floor level on the NW façade and at ceiling level on the SE façade, which produces an internal stack; there are no wind effects.

– **internal and external stack** - continuous openings at floor level on the NW façade, high openings into three storey high chimneys on the SE façade, no wind effects

– **internal stack + wind** - continuous openings at floor level on the NW façade and at ceiling level on the SE façade. The flow is produced by a combination of wind and internal stack effects.

– **internal and external stack + wind** - continuous openings at floor level on the NW façade, high openings into three storey high chimneys on the SE façade. The flow is produced by a combination of wind and internal and external stack effects.

A representative 9m section of one open plan office floor was modeled as a single thermal zone, including the appropriate internal and solar heat gains. The external chimney, when present, was modeled as a second thermal zone, as shown in Figure 4. A discharge coefficient of 0.5 was assumed for each opening (a conservative value that allows for pressure drop through the scrim). Initially, pressure coefficients were estimated from data in Chapter 15 of the ASHRAE Handbook of Fundamentals (ASHRAE 2001). Later runs used pressure coefficients measured using a scale model in a wind tunnel; no significant changes in thermal performance resulted from using the experimentally determined coefficients in this case.

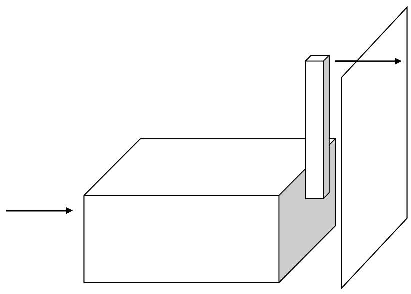

Figure 4: Two zone model of a section of one floor with an external chimney.

A semi-transparent detached shading element is used to model the on-axis transmission of the metal scrim. The off-axis optical properties of the perforated metal scrim were simulated using overhangs and side-fins to produce a rectangular reveal that has approximate geometrical similarity to the circular holes in the scrim. The different ventilation configurations were simulated for the period April 1 to October 31 of the TMY2 composite weather year for San Francisco International Airport.

The windows are opened whenever the inside air temperature exceeds both the set-point and the ambient temperature.

Comfort Criteria

The client (the US General Services Administration) accepted the proposal of the design team that the naturally ventilated portions of the building should have comfort criteria based on the adaptive model currently being added to ASHRAE Standard 55 (Braeger and de Dear 2000), which links the indoor comfort temperature to the mean monthly outdoor air temperature. The upper limit of the 80% acceptable range of indoor operative temperature is 79-82^{o}F for the cooling season (April 1 – October 31). The extension to ASHRAE Standard 55 does not account for humidity; however, the maximum value of the ambient dew point in the San Francisco TMY2 is 15^{o}C and the typical daily maximum value in the summer is ~12^{o}C, so humidity does not have a significant influence on comfort if the internal latent gains are small, as they are in offices. The adaptive model assumes that occupants will change their clothing and metabolic rates (within limits) in response to changing conditions in order to maintain comfort.

Simulation Results

Operative temperature, which is an average of the dry blb and mean radiant temperatures, is used as an indicator of thermal comfort. The performance of the different strategies was evaluated by predicting the number of ‘degree hours’ above selected base temperatures during occupied hours and the results are shown in Table 1. The case in which the building is completely unventilated is presented for comparison. The main observations are:

1. Wind-driven night ventilation produces reasonable comfort conditions during the day for all but a few days of a typical year.
2. Internal stack-driven night ventilation resulting from low level openings on the NW and high level openings on the SE is less effective than wind-driven ventilation. Analysis of the simulation results shows that the internal temperature on hotter days is 0.5-1K higher than for the wind-driven case (see below).
3. A combination of wind-driven and internal stack-driven ventilation produces a modest improvement in performance compared to the wind-only case.

Table 1: Degree hours above various base temperatures

Basetemperature (^{o}C)	Wind only	Internal stack	Int & ext stack	Int stack + wind	Int & ext stack + wind	No ventil-ation
22.2	288	507	432	279	285	14561
23.9	80	118	103	76	76	8894
25.5	13	25	19	11	12	4284

4. Addition of external chimneys does not improve the performance of the combination of wind-driven and internal stack-driven ventilation, and may be slightly counter-productive, presumably due to the increased flow resistance caused by the chimney. In the absence of wind, addition of external chimneys helps the internal stack somewhat.

The operative temperature exceeds 25°F on six particularly hot days during the typical year, when the maximum ambient air temperatures are in the range 30-35°C. Figure 5 shows the performance of the different strategies on one of these days, July 3, 1970, which was the third day of a sequence of three extreme days. The preceding two days had maximum temperatures of 30°C and 35°C. As a result, the building is not significantly pre-cooled at the beginning of the occupancy period. The rise in internal temperature during the first eight hours of occupancy is limited only by the thermal capacity of the building, since the outside temperature is too high for ventilation to be useful.

Figure 6 shows the performance on a more typical warmer day, June 16, 1971 (the eleventh hottest day in the typical year). The building has been significantly pre-cooled overnight, possibly excessively so. The relative performance of the different strategies is essentially the same as that on July 3, in spite of the night-time ambient temperature being significantly lower, relative to the interior temperatures, which would be expected to give rise to greater buoyancy-driven ventilation rates. It may be noted that, since the building is already slightly overcooled at the beginning of the day, the performance during the afternoon is limited by a combination of the available thermal capacity and the effectiveness of the solar control. This is because the ventilation rate during the day is kept low because the ambient temperature is high.

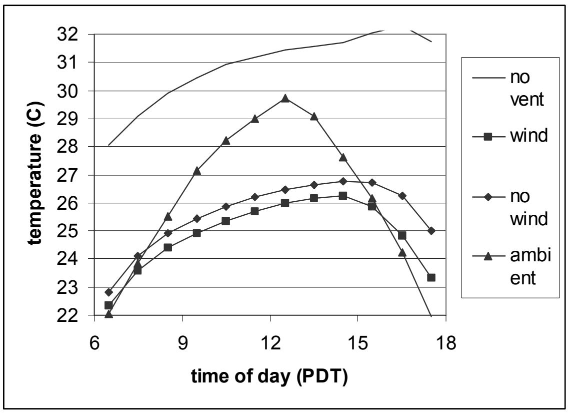

Figure 5: Predicted operative temperature for different ventilation strategies on July 3. The various strategies that involve wind are indistinguishable from each other and are indicated by 'wind'; the strategies that involve only buoyancy are also indistinguishable and are indicated by 'no wind'. The case of no ventilation is shown for comparison.

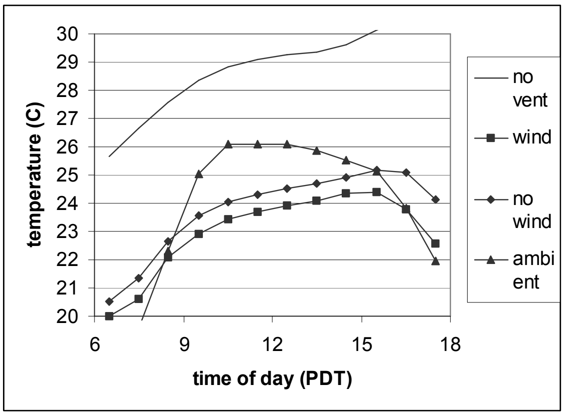

Figure 6: The operative temperature for the different ventilation strategies on June 16.

CFD ANALYSIS

Detailed analysis of the ventilation performance of a typical naturally ventilated floor allowed for fine tuning of the design. It provided predictions of the cross flow ventilation (CV) airflow pattern, the maximum velocities in the occupied volume of the workspace, and the ventilation efficiency and ventilation flow rates for variable wind conditions. The configuration of the ventilation apertures in the façade and the office furniture design were tuned as a consequence of this study.

The first step in the analysis was to simulate the internal CV flow, using the geometry shown in Figures 2 and 7. The simulated region was one quarter of the naturally ventilated portion of a typical floor. This reduced simulation region is possible because of the symmetry and repetition of the floor plan of the building. The simulation domain spans one half of one side (specifically the NE half of the NW side of a typical floor). The two facades have symmetric upper and lower openings, consisting of rows of top hinged windows (see Figure 2).

Workstation furniture was inserted, according to specifications provided by the designers (Christ, 2002), allowing both for a more realistic simulation and for testing of the furniture configuration, in particular the use of porous vertical furniture panels. The ceiling is corrugated concrete with a sinusoidal cross-section. This curved geometrical feature was simulated in an approximate way, using stacked parallelepiped shapes.

The CFD domain included a region around the building in order to reproduce the behavior of the wind driven airflow as it comes through the windows. The simulations were performed using a

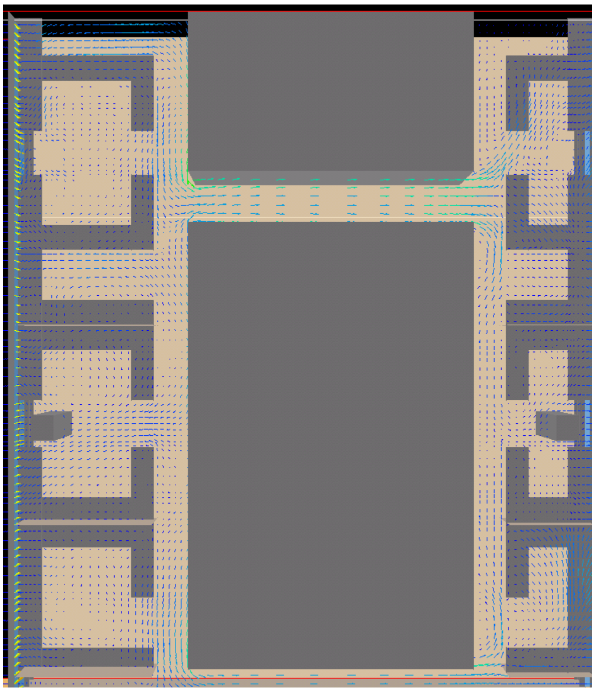

Figure 7. Case 1, bottom view, z=1m. The NW wing is on the left and the SE wing is on the right. The gray rectangle in the upper center of the figure is the service core and in the middle and lower center is the meeting room.

commercial CFD package, (PHOENICS, 2000). Simulations were considered converged when the normalized residuals were smaller than 10^{-3} and the solution field was stable: i.e. the values did not change by more than 10^{-7} (relative change) between iterations, and showed no visible fluctuation or changes after hundreds of iterations. The effects of turbulence were modeled using the standard k-ε model. Results of simulations for different flow rates showed a linear variation of the air speeds in the room with inlet speed, as expected (Carrilho da Graca *et al*., 2003).

Table 2 shows the general characteristics of the cases analyzed. The column labeled: "%opening used" is the open area as a percentage of the total available opening area for each configuration.

The result of the simulation using this geometry and a $1 ms^{-1}$ external NW wind (perpendicular to the facade) is shown in Figures 7, 8a, 8b and 8c. The dominant aspect of the predicted flow is the large recirculation zones in the occupied regions of the space. The inflow jet enters from the two windows (lower and upper, see Figures 2 and 8) attaches to the ceiling and exits through the SE bay. This flow pattern is very effective in two respects: ensuring significant cooling of the ceiling slab with night time wind-driven airflow, and avoiding high velocities in the occupied zone during the day.

Table 2 - Cases analyzed.

Case	Upper Opening	Lower Opening	opening used (%)	Furniture panels
1	All open	All open	100	Standard
2	All open	All open	100	Porous
3	All open	All closed	66	Standard
4	Half open	All open	77	Standard
5	Half open	All closed	45	Standard

This first simulation revealed that the expected problem area behind the service core is well ventilated, showing no significant stagnation. When the windows on the leeward side are open, accumulation of heat and pollutants does not occur: the air flow in the adjacent corridor and over the meeting rooms is drawn towards the open windows.

In order to understand the effect of user operable windows on the flow pattern, a second simulation was performed with the user operable windows closed (case 3). Figure 8d shows a side view of the flow in the NW zone behind the meeting rooms and the service core for this case. Comparison of Figures 8c and 8d indicates a problem: the user-controlled window does not significantly affect the airflow in the occupied region.

This qualitative analysis was confirmed after post processing the results of these two cases. The average speed in the occupied zone only increases by 18% when opening the user-controlled lower opening. Opening the window does not significantly affect the flow pattern and the existence of the strong vertical recirculation region leads to accumulation of heat and pollutants in the windward bay. With this initial window geometry, the users on the windward side do not experience a significant changes in their local environment when opening the window, possibly leading to poor window operation decisions and consequent decreased cooling performance.

This first analysis revealed two aspects that could be improved. The flow from the operable windows could be better directed, improving ventilation efficiency. Also, given the windy climate of the site and the ratio between average indoor and outdoor wind velocities, there is the possibility of reducing the maximum opening area.

Design of an inflow deflector for the user operable windows

In order to improve the heat and pollutant removal efficiency an inflow deflector for the user operable windows was designed. The flow deflector is incorporated in the bottom element of the moveable part of the window.

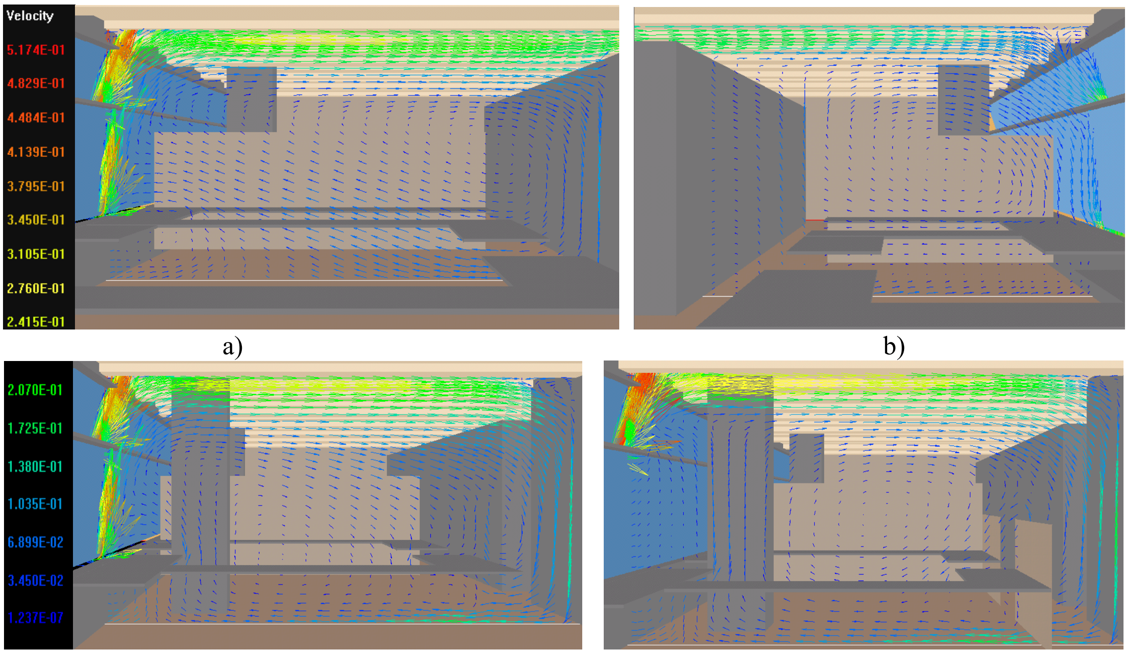

Figure 8. Side view of the velocity field (m/s) in the NW (a), c) and d)) and SW (b)) wings. a) Flow in the NW bay, in a section spanning over a meeting room, all windows open; b) Flow in the SE bay, in a section spanning over a meeting room, all windows open; c) Flow in the NW bay, in a section obstructed by a service core, all windows open; d) Flow in the SE bay, in a section obstructed by a service core, user operable windows closed. The main effect of the service core obstruction is to increase the recirculation flow on the NW side..

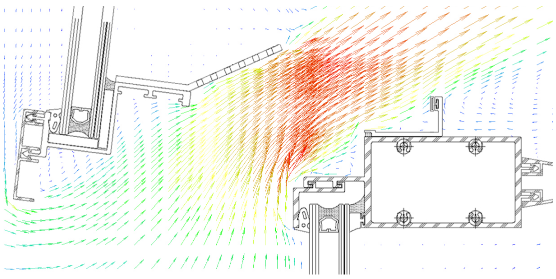

Figure 9. Simulation of the final design for the flow deflector.

The inclusion of the flow deflector disrupts the recirculation by avoiding the attachment of the inflow through the lower window to the glass surface directly above the opening. It is desirable that the user operable opening has the maximum possible momentum flux, increasing its ability to affect the flow in the occupied zone, as discussed in the previous sections. An initial deflector design (not shown) led to a reduction in the opening area that reduced the overall opening area and diminished the influence of the lower opening on the flow in the occupied zone. In order to avoid these effects, several options where analyzed. Figure 9 shows the final deflector configuration, which significantly deflects the flow while allowing an adequate opening area.

Analysis of window opening requirements

A wind climate analysis shows that there is abundant potential for wind-driven ventilation. This is a consequence of both the base climate conditions and the good exposure and orientation of the façade. The building is sufficiently ventilated even with low wind velocities and, due to its particular geometry, small improvements in indoor flow distribution can have a significant impact on the efficiency of the ventilation system. An analysis of opening sizes and ventilation rates was performed, with the goal of identifying possibilities for reducing and simplifying the opening geometry. The analysis was performed by applying the orifice equation to each opening, using a value for the discharge coefficient for flow through a sharp edged opening of 0.62.

The results, for external NW wind, are shown in Figure 10. The relatively small reduction in percentage of opened area between Cases 1 and 3 (see Table 2) results from the fact that, when only half the windows are open, air flows through the triangular spaces on the side of the opening. With adjacent openings there is no flow through these spaces.

The reduction in flow rate that results from using only one half of the top window openings is not significant. Winds stronger than 2 ms^{-1} are very frequent, and for this wind speed, only the most

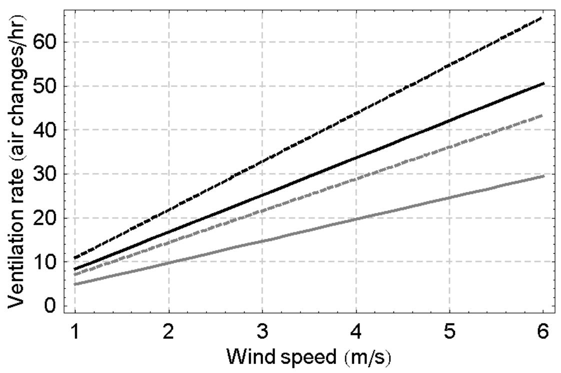

Figure 10.Variation of ventilation rate with wind speed (Cp=0.9). Black dashed line: Case 1 (100%). Gray dashed line: Case 3 (66%). Black line: Case 4 (77%). Gray line: Case 5 (45%).

closed configuration (Case 5) results in less than 10 air changes per hour. A NW wind of 3 ms^{-1} induces 22 or 16 air changes per hour when all the top windows or just one-half of them are open (Cases 3 and 5 in Table 2), respectively.

The analysis indicates that opening only half of the top windows, in combination with an improved airflow pattern, results in good ventilation. The upper windows are motorized, so this reduction has cost benefits. The use of alternating open and closed elements at the top of the exterior wall disrupts the two dimensionality of the system, contributing to increased mixing. As will be seen in the next section, the recirculations are still vertical, but become slightly less pronounced.

Effects of variable opening and office furniture configurations

CFD simulations were run, in order to investigate on possible negative effects of closing half the upper windows on the airflow pattern. The adoption of alternating open and closed elements required additional CFD simulations in order to investigate possible negative effects on the airflow pattern. The concerns were possible variations in air speed along the ceiling slab, caused by the non-uniform distribution of inlets, and the possibility of negative effects on the flow on the occupied zone, such as a significant air speed reduction.

Figure 11 shows the average air speed in the occupied zone, normalized using outside wind speed, for NW incidence and Cp = 0.9 for Cases A to D. The variations in average velocity when opening the lower windows are very small (Cases A and C in the figure). This is also the case shown in Figure 10 (Case D). The small reduction in occupied zone velocity is not significant, and can be easily offset by increase mixing and the improvements in airflow pattern that will be discussed below.

One of the many innovations in the design of the building is the specification of workstations/office furniture that are not only easily integrated in the space but also enhance the indoor environment. The furniture specifications produced by the building designers included:

1. Variable height in furniture panels depending on orientation (lower height for elements perpendicular to the mean flow).
2. A gap between the furniture panels and the floor (minimum 0.2m).
3. Porous furniture panels (the porous panels are perpendicular to the cross ventilation flow and are meant to allow for light and air to flow through them). In order to improve privacy and acoustic insulation between adjacent workstations, porous panels were not used in the elements parallel to the mean flow.

The specified workstation geometry was included in the simulations. In addition, a simulation was performed to test the effects of porous panels. After preliminary simulations revealed that flow through the panels was small, it was decided to use the most porous sample: a woven screen regular mesh, with a yarn width of 0.1mm and a porosity of 90% (Miguel, 1998).

The two main features of the flow around the workstations are: (i) the flow through the porous panel is small, and (ii) the flow accelerates under the vertical panels, leading to the highest speeds that can be found in the occupied space (in the windward zone).

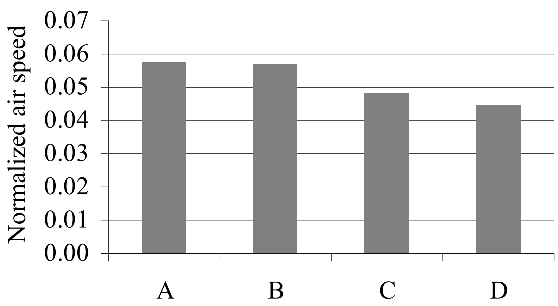

Figure 11. Normalized average air speeds for different configurations: A-normal fully open windows, B- same as case 1 but using porous furniture panels (90%, Yarn width 0.1mm), C-same as 1 but with lower windows closed, D-same as case 1 but with one-half of the upper windows open. In all cases, the regions with maximum velocity in the occupied zone were close to the floor and had average velocities of approximately three times the occupied zone average.

The average velocity on the occupied zone in the simulation using porous panels is shown in Figure 11, case B. The effect of the panels in increasing flow in the occupied zone is negligible. This result is not surprising: air will always tend to flow through the unobstructed spaces of the occupied zone, and there are many areas where this unobstructed flow is possible. Any resistance to airflow leads to a deflection of the flow path into unobstructed zones, areas with no panels and the gaps between the panels and the floor.

CONCLUSIONS

A purely wind-driven ventilation strategy was selected for the building, based on the following results of a design analysis using EnergyPlus.

1. Natural ventilation is able to produce a level of thermal comfort that is likely to be acceptable to the occupants for all but a modest number of hours in a typical year.
2. Wind-driven ventilation slightly outperforms buoyancy-driven ventilation for the same opening sizes for this particular site.
3. On all but a few days, the nocturnal cooling of the building has to be limited in order to avoid uncomfortably cool conditions at the start of occupancy. The cooling performance of the building is then limited by the available thermal capacity and the effectiveness of the solar control, particularly on the NW façade.

The computational fluid dynamics simulations then led to several significant design changes.

1. Reduction in the amount of opening area used.
2. Change in the geometry of the automated opening area to alternating operable and fixed windows.
3. Change in geometry of the user controlled operable windows by introducing a flow deflector.

This airflow study reported here formed the basis for the design and testing of control strategy for the natural ventilation system, as described in a companion paper (Carrilho da Graça *et al.*, 2003).

The simulations and analysis presented here have resulted in increased confidence in the performance of the passive cooling and natural ventilation systems of the building as well as improvements to the design.

ACKNOWLEDGMENTS

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California Energy Commission
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HPCBS

High Performance Commercial Building Systems

Design and Testing of a Control Strategy for a Large, Naturally Ventilated Office Building

Element 4 Low Energy Cooling

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DESIGN AND TESTING OF A CONTROL STRATEGY FOR A LARGE, NATURALLY VENTILATED OFFICE BUILDING

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ABSTRACT

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. Each floor is designed to be cross-ventilated, through upper windows that are controlled by the building management system (BMS). Users have control over lower windows, which can be as much as 50% of the total openable area. There are significant differences in the performance and the control of the windward and leeward sides of the building, and separate monitoring and control strategies are determined for each side. The performance and control of the building has been designed and tested using a modified version of EnergyPlus.

Results from studies with EnergyPlus and CFD are used in designing the control strategy. EnergyPlus was extended to model a simplified version of the airflow pattern determined using CFD. Wind-driven cross-ventilation produces a main jet through the upper openings of the building, across the ceiling from the windward to the leeward side. Below this jet, the occupied regions are subject to a recirculating airflow. Results show that temperatures within the building are predicted to be satisfactory, provided a suitable control strategy is implemented uses night cooling in periods of hot weather.

The control strategy has 10 window opening modes. EnergyPlus was extended to simulate the effects of these modes, and to assess the effects of different forms of user behavior. The results show how user behavior can significantly influence the building performance.

INTRODUCTION

The control system development study presented in this paper continues previous work (Haves *et al*, 2003) on the design of the natural ventilation system for the new San Francisco Federal Building (SFFB). The definition of the control strategy for the natural ventilation system is critical to achieving good performance in the building. The requirements for this control strategy are:

- ability to control air speed in the occupied space;
- effective use of the building internal thermal mass for cooling;
- rational use of heating energy;
- control of indoor conditions during storm, rain and high wind periods;
- unintrusive and as simple as possible.

COMPONENTS OF THE INDOOR CLIMATE CONTROL SYSTEM

Figure 1 shows a section of a typical floor of the naturally ventilated portion of the building. In an earlier phase of the work, reported in a companion paper (Haves et al, 2003), it was determined that the favorable wind climate that exists in San Francisco produces sufficient cross-ventilation to maintain acceptable comfort. During episodes of hot weather, the building is ventilated at night to cool the exposed concrete ceiling slab, which serves as a heat sink for daytime heat gains. Buoyancy forces have a minor effect on the airflow in cooling mode.

Heating is provided by a perimeter baseboard system. There are nine trickle vents under selected baseboards on each bay, on each side of each floor. The main NW and SE facades are ~100% glazed. Although the windows on the SE façade are shaded by an external metal scrim, there is a significant amount of passive solar heating from these windows at the beginning of the day.

The building is controlled by a combination of user and automated window operation. The BMS has exclusive control over the baseboard heating system. As discussed below, the users can significantly change the total opening area, affecting the results of the automated control actions exerted by the BMS. In

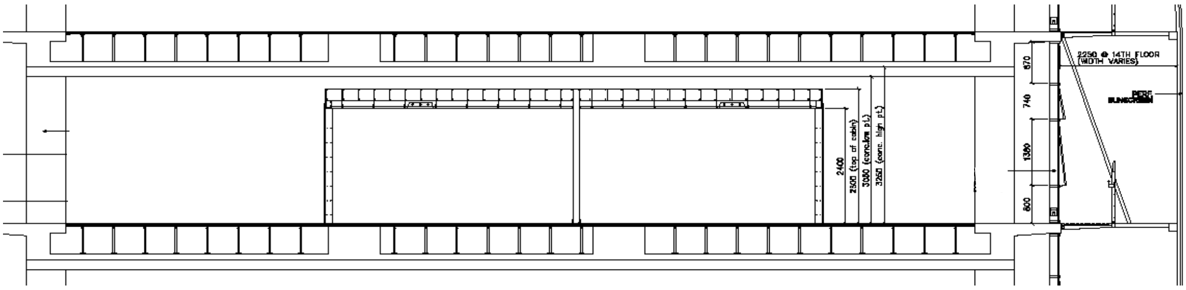

Figure 1. Section of a typical floor of the SFFB.

A section showing the NW bay (left), the SE bay (right) and the air-conditioned meeting rooms (middle). The lower operable windows visible in both bays are controlled by the users. The upper windows are controlled by the BMS. The user operated windows open 10cm, the BMS operated windows open 20cm. There are two user operated windows for every BMS operated window. There is a perforated stainless steel shading scrim that covers the South-East façade of the building.

order to avoid continual control actions, which may be distracting for the occupants and cause unnecessary wear, the BMS will make adjustments approximately every 10 minutes. The exact interval will be determined as part of the process of commissioning the building.

VENTILATION STRATEGY

Whenever the wind induced pressure is higher on one side of the building, air will flow into that side and out of the opposing side. The previous natural ventilation airflow analysis revealed an important characteristic of the crossflow ventilation (CV) airflow pattern. The incoming air attaches to the ceiling and partially "short circuits" the occupied zone of the windward bay, exiting through the windows in the leeward facade.

The proposed geometry of the user operated windows contributed to this short circuit effect, generating an inflow jet that attached to the windward user windows and joined the jet entering through the windows operated by the BMS. As a result, the windward side (WS) users had limited control over their local environment. This problem was addressed by proposing changes to the geometry of the user operable windows based on a CFD analysis of the airflow through the window (Linden *et al*, 2002). A flow deflector, which directs the inflow from these openings into the occupied zone, was introduced. The flow pattern produced by the initial design resulted in leeward side (LS) users suffering the consequences of the control actions taken by WS users. With the WS users able to adjust their local flow conditions, by opening and closing a window that directs flow to their work area, the BMS can more easily address the needs of the LS users, using the short circuit of the air entering through the upper windows to produce a beneficial independence between the two sides (see Figure 2).

In addition to this separation, and as a result of the approximately symmetrical layout of the floor plan, we decided to simplify the control strategy by defining it in terms of Windward and Leeward, as opposed to NW and SE. Table 1 shows the four possible states that result from this approach. By basing the control system on the wind direction, the number of system states is significantly reduced.

Care was taken to avoid air that had been heated by the baseboard system on the leeward side being exhausted through the adjacent trickle vents. For this reason, whenever the heating is on, only the trickle vents on the windward side are opened. Since height between the BMS and user operable windows is modest, stack driven ventilation is only important when the wind velocity is very low or parallel to the long axis of the building and the trickle vents are open.

Table 1. The four possible states of the occupied spaces on a particular floor during building operation hours.

WINDWARD	LEEWARD
Warm	Warm
Cold	Cold
Cold	Warm
Warm	Cold

Figure 2a shows the floor subdivision used to define the control zones. The basic control unit is one half of a floor (each floor has two BMS zones, one for each set of five "slices", numbered 1-5 in Figure 2a. The labels: W and T stand for window (user operable) and trickle vents (under the baseboard system). The window opening strategy reflects the fact that the geometry of the inflow openings governs the airflow distribution and the consequent effectiveness of the removal of pollutants across the whole width of each

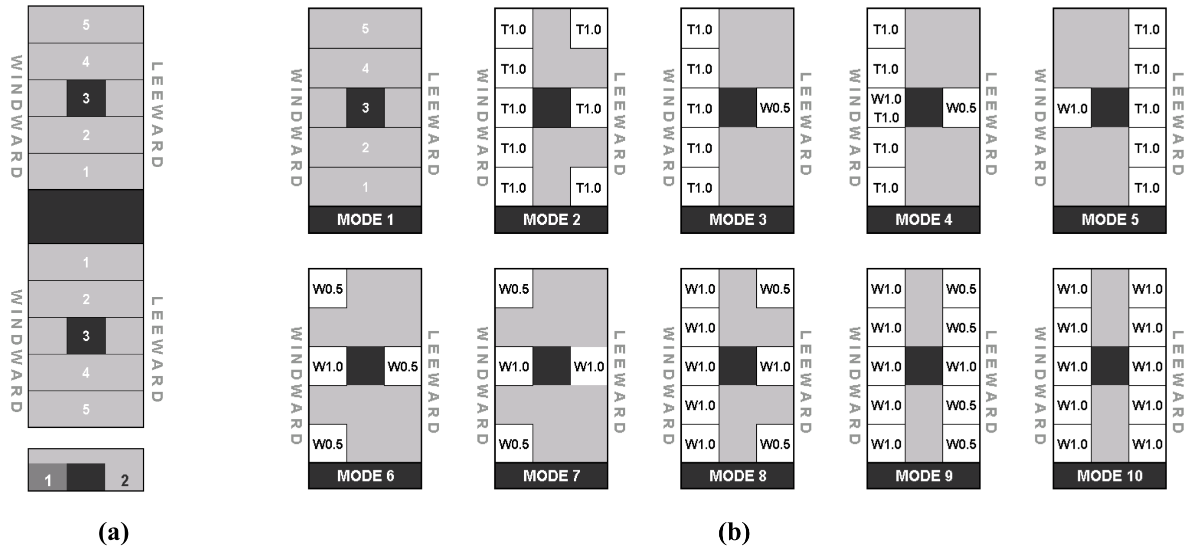

Figure 2.

a) Schematic layout of the control system on a typical floor. Each floor measure approximately 107x19m. Each half of each floor in the building is treated separately (in the figure, each set of 1-5 “slices”). Each slice contains four user operated and two BMS operated windows. The side view at the bottom of the figure shows the control structure, using the partial short circuiting of BMS window inflow into the windward zones (labeled 1). b) Schematic representation of the aperture modes. Each floor of the building is divided into two symmetrical sides. The figures show one half of one floor. The black square in the center of the figures is an elevator/service core that creates an obstruction to cross-ventilation airflow.

side of the naturally ventilated part of the floor. The criteria used in defining the opening modes were:

- use distributed inflow openings to spread the inflow across the floor plan and reduce local velocities;
- use the outlet area to control the flow rate;
- minimize operation of openings (by ensuring continuity between opening modes, avoiding open-close-open sequences as the system increases opening area);
- minimize the number of window positions, in order to simplify the mechanical actuator system (three positions are used: closed, half-open and fully open).

The airflow control strategy was structured in an opening mode table, and the twenty BMS operable windows in each bay of the floor (two per “slice”, five “slices” on each side, leeward, windward), were grouped for simplicity. The grouping criterion was optimal flow distribution. Figure 2b shows a schematic representation of the ten opening modes used. The positions of the openings are shown as fraction of maximum opening size (between zero and one).

There are two groups of trickle vents on each bay: “slices” 1, 3 and 5, and “slices” 2 and 4. The window groups are: Group 1 containing the two motorized windows in slice 3, Group 2 contains the four motorized windows in slices 1 and 5 and Group 3 contains the four motorized windows in slices 2 and 4. Modes 3 and 4 use the windows on the leeward side, in slice 3, to avoid exhaustion of warmed air through the leeward side trickle vents.

A mode table was organized in order to contain the opening modes ordered by effective opening area and weather/defensive criteria (see Tables 2 and 3 for grouping and characteristics of the modes). In Table 2, the column labeled “Open” refers to effective opening area. For a given pressure difference (ΔP), the effective opening area A* and resultant flow rate are given by

$$F = A^* C_D \sqrt{\frac{2\Delta P}{\rho}}, \tag{1}$$

where

$$A^* = \sqrt{\frac{A_W{}^2 A_L{}^2}{A_W{}^2 + A_L{}^2}}.$$

The estimates of the indoor ventilation parameters A_W/A_L, V_{IN} and V_{OZ} presented in Table 2 show that the system has the desired characteristics, listed above. There is a continuous increase in opening size in each group of modes (see Tables 2 and 3). There is a set of modes that controls the inflow and average occupied zone velocities (Modes 5-8); Modes 9 and 10 are meant to be used when the wind is weak, or at night, when significant transfer between indoor air and the ceiling concrete slab is desirable.

Table 2. Characteristics of the opening modes. A_W is the opening area on the windward side, A_L is the opening area on the Leeward side, V_{IN} is the average velocity at the inlet on the windward side, using (1), for a 10m/s outside wind, a pressure coefficient of one and a discharge coefficient C_D of 0.6), V_{OZ} is the predicted average velocity in the occupied zone (from CFD, for a 10m/s outside wind and a pressure coefficient of one), and Open is the ratio of the effective opened area to the maximum effective area,

Mode	A_W/A_L	V_{IN} (m/s)	V_{OZ} (m/s)	Open (%)
1	-	-	-	0
2	2.0	2.7	0.89	3.4
3	0.5	-	-	6.7
4	1.3	3.8	-	22.2
5	3.7	1.6	0.53	7.3
6	4.0	1.5	0.50	13.7
7	2.0	2.7	0.89	25.3
8	2.5	2.3	0.76	52.5
9	1.7	3.1	1.02	72.8
10	1.0	4.3	1.42	100

Although the users have access to operable openings, it was decided that the BMS system would ensure 50% of the regulatory minimum outside air flow. The remainder will be provided by infiltration and the users, through their operable windows. Consequently, upper and lower limits are placed in the opening mode number depending on limiting factors: a lower limit is used in order to ensure minimum outside air, an upper limit is used whenever the wind is strong, during rain periods or when the baseboard heaters are turned on in both bays.

The first high wind opening limiting mode is triggered by:

> *If* ΔP>60 or Vwind>20m/s *then* the mode number cannot go above 8.

The second high wind opening limiting mode is triggered by:

> *If* ΔP>130 or Vwind>25m/s *then* the mode number cannot go above 6.

The storm mode is triggered by:

> *If* ΔP>300 or Vwind>30m/s *then* the mode number cannot go above 2.

Additional rules include:

> *If* heating is on in both bays, *or* it is raining *then* the mode number cannot go above 4.

> *If* both sides are in cooling mode *then* the mode number cannot go below 5.

Table 3. Division of the ten modes in three groups.

Situation	MODES
Storm	1 , 2
Heating/Rain	3 , 4
Mild/Cooling	5 , 6 , 7 , 8 , 9 , 10

INSURING MINIMUM OUTSIDE AIR

With the objective of having the BMS system ensure 50% of the minimum outside air, we establish a decision process based on:

1. the measured the outside pressure difference ΔP;
2. an estimate of stack pressure (whenever the trickle vents are open, in the current control system, this is equivalent to the heating being turned on, see modes 2-4 in figure 1);
3. the fluctuating wind velocity pressure (in order to prevent excessive opening size when the wind is parallel to the building and the average pressure difference measurement (ΔP) is close to zero but the transient ventilation is significant).

The BMS estimates the total available pressure and determines the minimum opening size and the corresponding mode numbers between 3 and 10. When there is a storm (the system is in Modes 1 or 2) we rely on infiltration and user adjustment to provide minimum outside air. Buoyancy will only be considered when the heating is on in both bays (which implies the trickle vents are open).

The total pressure difference (ΔP_T) available to drive the flow is the sum of the pressures discussed above

$$\Delta P_T = \Delta P + HOF\left(0.088\left|\frac{T_W - T_L}{2} - T_{OUT}\right|\right) + 0.015\ U_{WIND}^{\ 2} \qquad (2)$$

where U_{WIND} is the outside wind speed and HOF is a software "flag" that signals the buoyancy component should be considered.

The third term in (2) is based on an experimental correlation for airflow in a building exposed to an incoming wind parallel to equal openings on opposed envelope surfaces (Etheridge, 1979). In order to simplify the estimation of ΔP_T, the effects of unequal opening areas on the two bays are ignored. In addition the transient pressure (third) term is not dependent on wind direction. This is an acceptable approximation because, whenever the wind is not parallel to the openings, the first term is an order of magnitude larger.

IMPACT OF USER WINDOW CONTROL

The user operable window area is approximately equal to the BMS controlled area; therefore, users can significantly change the total effective opening area (see (1)). The lower windows are exclusively under user control, and users can, for example, increase the effective opening size ten times when the system is in Mode 5 or approximately double the effective area when in Mode 10.

If user control is not considered when designing the control strategy, two main problems can occur:

(a) users on one of the two sides could significantly affect the climate control on the other side, and

(b) incorrect user control could lead to poor overall system performance, producing overheating of the interior space and concrete slab in summer, and allowing heat to escape to the outside in winter.

The impact of user opening level on the effective opening area decreases with increasing opening mode number. On warm days, whenever the control objective is to make optimal use of the cooled concrete slab, user opening can result in higher, and often uncomfortable, indoor temperatures.

Clearly, the more general consequences of user behavior cannot be addressed by the control system. Therefore, appropriate information on building behavior and on adequate actions in different situations must be provided to the users.

By controlling the airflow rate using the size of the outlet, and by making the flow controlled by WS users affect primarily the WS users, significant automatic control over the conditions of the LS users was achieved. When WS users open their windows, the overall flow does not change significantly if the high level WS windows are already open. However, when these users open their windows, the existing airflow and inflow is partially displaced from the upper (BMS controlled) openings to the user operated windows (in the proportions of the relative opening areas). In this way, the WS users achieve the desired change, more outside airflow through their working area, without significantly changing the leeward side conditions.

However, adjustments by the LS users have a significant effect on the airflow rate. In view of the previously mentioned partial short circuiting of the inflow and the ability of WS users to adjust their local conditions, we conclude that the asymmetry in flow control is a beneficial feature of the system.

MODELING USER BEHAVIOUR

Modeling user behavior is a complex but essential task for the present study. In order to simulate the performance of the indoor environment control system with both BMS and user actions, two types of user behavior were defined.

● Uninformed users (UU): this type of user is modeled so that user behavior is totally independent of BMS actions. If the conditions are warm, the user operable windows open sequentially (10% in each control time step, 10 minutes), up to 50% for indoor temperatures between 22 and 25^{o}C, and up to 100% for temperatures above 25^{o}C. If the conditions are cold, below 19^{o}C, the user operable openings close by 5% each time step. On a typical day, when the air temperature in either of the two bays goes above 22^{o}C, users will open the windows, the windows will then remain open until the temperature on one of the sides drops below 19^{o}C, or until the end of the workday, when users always close their windows.

● Informed users (IU): this type of user follows the BMS actions in an ideal way. Users only open their windows when the BMS is in one of the mild modes. Informed users follow the same decision and action trends as uninformed users but limit their opening amplitude in accordance to the BMS mode that is currently being used (linearly, from 0% in Modes 1-5 to 100% in Mode 10). In addition, whenever the BMS system uses night cooling, informed users will leave their windows fully opened overnight.

These two user behavior scenarios allow us to model overall control system performance (users with BMS) in two extreme situations: positive and negative interaction between users and the BMS system.

CONTROLLING INDOOR TEMPERATURE

Table 1 showed the four temperature states that can occur in the two control zones of the building. We now proceed to describe and analyze the control strategies and rules used in each case.

Both sides cold. When both sides are cold, the heating system is on and the ventilation system will tend to minimum outside air in a progressive way, by reducing the window opening mode by one in each control time step.

Both sides warm. In order to clarify the control principles used during daytime in the warm season, we present here a first order analysis of system behavior. For this analysis we make two approximations.

(i) The only thermally active internal surface is the concrete ceiling slab. This approximation is adequate since the remaining internal surfaces in the space have low thermal mass and, therefore, tend to behave in an approximately adiabatic way, closely following the internal air temperature.

(ii) The internal air is fully mixed in each bay, which is a significant approximation that is only acceptable for a first order analysis. Also, for control purposes, during warm periods, the BMS system uses a single temperature (the highest of the two bays) to represent indoor conditions.

In these conditions, the equation that represents energy conservation in a control zone (one half of one floor, see Figure 2) is

$$h\,A_S\left(T_{IN}-T_S\right)+\rho c_P\,F\left(T_{IN}-T_{OUT}\right)=G\,, \qquad (3)$$

where h is the average heat transfer coefficient, T_{IN} is the fully mixed indoor temperature, T_S is the concrete ceiling slab average surface temperature, T_{OUT} is the outside temperature, c_p is the heat capacity of air at constant pressure, ρ is the density of air, F is the volumetric flow rate and G is the sum of the other heat gains (solar, internal and heat conduction through the envelope). The solution to (3) is

$$T_{IN}=\frac{1}{1+\theta}\left(T_S+\theta T_{OUT}+\frac{G}{h\,A_S}\right) \qquad (4)$$

where $\theta = \rho c_p F/hA_S$ is the normalized air flow rate.

Once a building is in operation, all the temperatures in this expression can be measured and used to make decisions on the single adjustment parameter available, the flow rate F. The gains, the value of the heat transfer coefficient and exposed area are generally unknown, although, in an office space in mild climate, we expect the gains to be positive during the mild/warm season.

Qualitative analysis of (3) reveals that when F is increased, the parameter θ increases and T_{IN} tends to T_{OUT}. Conversely, decreasing θ brings T_{IN} closer to T_S. The unknown parameter G influences internal conditions (increased G results in increased T_{IN}), but, by measuring T_{IN} we can obtain an indirect measurement of G, and there is no decreased control ability from not knowing the internal gains. Table 4 presents the warm weather control rule map that was used.

Windward cold, leeward warm: as seen in the simulation results below, this situation often occurs in the early morning of the winter and mild season days. This is one of the situations where the interaction between the two sides must be considered. To meet the need for cooling in the leeward side the ventilation mode is increased by one. In order not to increase the cooling needs of the LS users, but still address the need for heating on the windward side, the windward heating set point is set to 18°C.

Windward warm, leeward cold: this case is the contrary of the previous case, but is not as problematic because the WS side users can address their needs by opening their user window (increasing local flow rate) without greatly affecting the overall flow rate. For these reasons, in this situation, the control system will reduce the aperture mode by one and set the leeward heating set-point to a relatively high value (21°C), to ensure heating on this side.

Night cooling: night cooling of the concrete ceiling slab will be done whenever the average indoor temperature during the warmer period of the day (11 am - 4 pm) is above 24°C. When night cooling is requested by the temperature control routine the ventilation system uses the maximum allowed opening mode until the slab temperature is below 19°C or until the early morning of the following day (7 am).

Table 4. Flow rate decision rules as a function of measured temperatures.

Situation	Flow
$T_{IN} > T_{OUT}, T_S$	Increase
$T_{IN} < T_S, T_{OUT}$	Maintain, or increase if cold
$T_{OUT} > T_{IN} > T_S$	Decrease if warm, increase if cold
$T_S > T_{IN} > T_{OUT}$	Increase if warm, decrease if cold

In future, the design team intends to incorporate weather prediction information in the control system, basing the decision to night cool on the next days predicted weather as well heat storage in the fabric during the previous day.

SIMULATION

In order to develop and test the low energy cooling system and its BMS control strategies, the behavior of the building and users was modeled using EnergyPlus, which incorporates the COMIS interzone airflow model (Huang et al, 1999). The model implemented to test the initial design principles (Haves et al, 2003) was the starting point for the model used in the simulations presented below. This model uses four distinct zones: the two bays (NW and SE), the meeting room in the middle of the floor plan and the space above the meeting rooms (see Figures 1 and 2). The simulation used pressure coefficients measured in a boundary layer wind tunnel (RWDI, 2002). Pressure coefficients representative of average wind exposure in the naturally ventilated portion of the building were chosen. Since only floors 6 and above are naturally ventilated, and adjacent buildings do not reach this height, all floors have sufficient wind exposure.

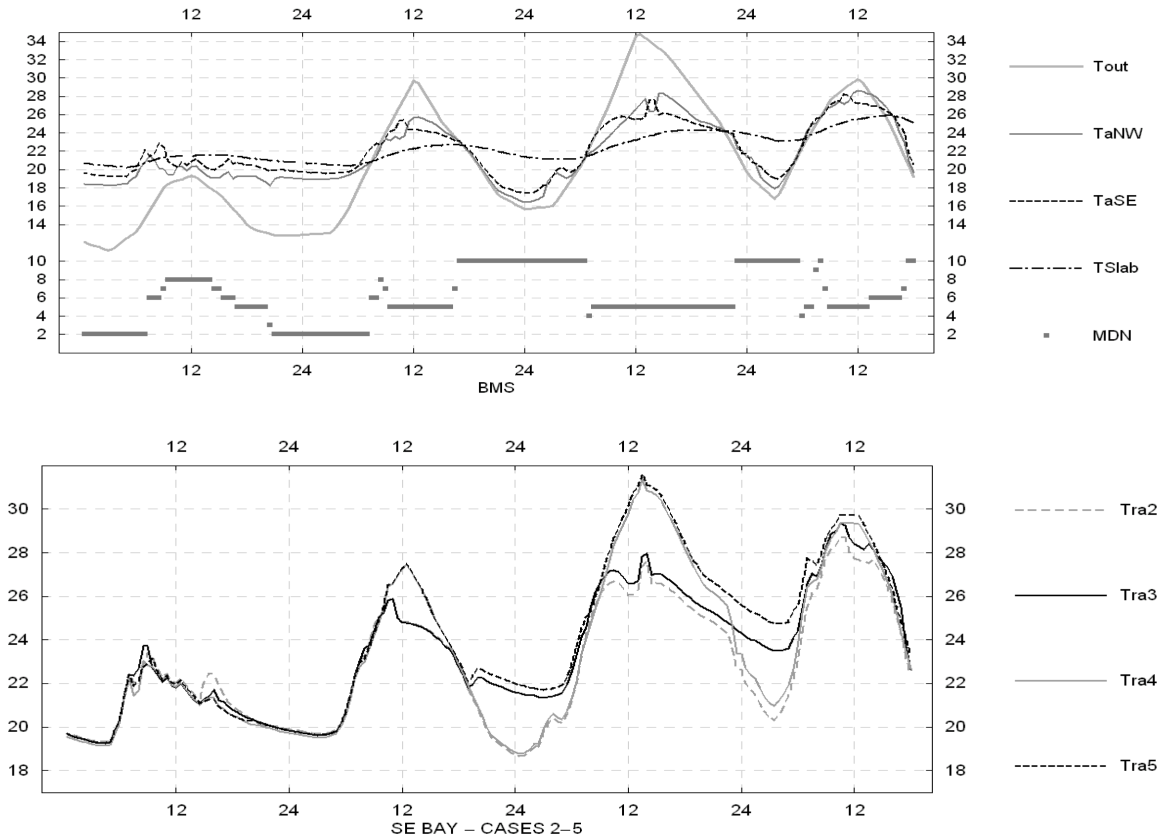

Figure 3. Predicted temperatures for case 1 in a sequence of warm days in July

All temperatures in ^{o}C. Tout: outside air temperature. TaNW: average air temperature in the North West bay. TaSE: average air temperature in the South East bay. TSlab: average surface temperature of the concrete ceiling slab. MDN: BMS system window opening mode. Tra2-5: the mean of drybulb air and mean radiant temperature temperature in the SE bay for cases 2-5.

The modularity of EnergyPlus allowed for the inclusion of a custom control subroutine (a module) that was used to simulate and tune the operation of the BMS system. The transmissivity of the metal shading scrim on the SE façade (see Figure 1) was set to 30%. The five cases simulated are shown in Table 5. Two typical mean weather years for San Francisco where used (a TMY and a TMY2).

Table 5. The five cases tested. First column: case number. Second: whether the case uses BMS control during the day. Third: whether the system uses night cooling. Four: type of user control, informed (IU), uninformed (UU) or no opening of the user operated windows.

Case	BMS	Night Cool	Users
1	Yes	Yes	No
2	Yes	Yes	IU
3	Yes	No	No
4	Yes	Yes	UU
5	No	No	UU

RESULTS

Figure 3 shows the predicted temperatures in the two bays and in the surface of concrete ceiling slab, for case 1 during a sequence of warm days in July. The results are plotted as 30 minute averages. The BMS system made decisions (turn on-off heating, change window modes) every 10 min. The first day shows typical behavior in a mild day. Between 10am and 2pm the BMS system uses outside air to remove internal heat gains. The second day is a typical warm day, and the BMS system selects the minimum daytime mild/warm mode (Mode=5). The air temperature in the SE bay (TaSE) has two phases during the day: above TaNW during the morning, as a result of solar gains in the SE façade, and below TaNW in the afternoon as a result of increased slab cooling effect in this bay. For NW incoming wind, the air moves in contact with the ceiling slab until it enters the SE bay. During the unoccupied night period of the second and third days shown, the system performs night cooling by selecting the maximum opening mode (Mode=10). The increase in slab temperature is visible. Temperatures labeled "ra" are the average "comfort" temperature (average of the mean radiant and air temperatures) in the two bays. As expected, air flows from NW to SE for a majority of the hours. The consequence of change in airflow direction is clearly visible at 1pm on the third day. As a result of a wind direction change the mean of drybulb air and mean radiant temperature changes, with a consequent increase in the SE as airflow cooled by the slab is replaced by warmer outside air.

Table 6 presents indicators of indoor climate control system performance for the five cases shown in Table 5. It is clear that uninformed users (cases 4 and 5) can have a significant negative impact in indoor climate conditions. According to our assumptions, uninformed users make limited use of the cooled slab and consequently warm their indoor environment. Because these conditions are not frequent, there is no substantial impact on system performance. Since the user operable area is comparable to the BMS controlled area, the impact extends to case 4. The absence of night cooling results in a 1K increase in the temperature on the warmest days.

Table 6. Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30°C.Columns labeled NW and SE refer to the two building bays. The cases correspond to those listed in Table 5.

	H >24°C		H >26°C		H >28°C		H >30°C	
Case	NW	SE	NW	SE	NW	SE	NW	SE
1	2.2	14	0.6	2.5	0.12	0.64	0.00	0.18
2	2.2	12	0.7	2.2	0.17	0.64	0.00	0.19
3	3.9	19	1.0	4.1	0.29	0.95	0.00	0.30
4	2.9	10	1.2	2.4	0.45	0.96	0.11	0.38
5	4.2	16	1.4	4.2	0.52	1.3	0.16	0.49

CONCLUSIONS

The results of the simulations show that the low energy indoor climate control system developed is expected to have excellent performance. The use of a window aperture mode table, in conjunction with the Windward-Leeward based control strategy, resulted in a clear and effective natural ventilation system. Analysis using simple heat balance calculations provides a basis for the simple temperature control strategy adopted.

Night cooling and optimal use of the chilled slab during the day is an appropriate strategy to deal with the warmest periods. As a result of the significant user controlled aperture area, the more general consequences of user behavior cannot be addressed by the control system. Clearly, information for the users on building behavior and on appropriate actions in different situations is important. However, simulations of different control strategies showed that the operation of the BMS always improves indoor conditions, even when occupant behavior is counterproductive.

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